

Modern Physics Letters A
 © World Scientific Publishing Company

PHYSICS OF DARK MATTER IN THE LIGHT OF DARK ATOMS

MAXIM YU. KHLOPOV

*National Research Nuclear University "Moscow Engineering Physics Institute" and
 Centre for Cosmoparticle Physics "Cosmion" 115409 Moscow, Russia
 APC laboratory 10, rue Alice Domon et Léonie Duquet
 75205 Paris Cedex 13, France
 khlopov@apc.univ-paris7.fr*

Received (Day Month Year)

Revised (Day Month Year)

Direct searches for dark matter lead to serious problems for simple models with stable neutral Weakly Interacting Massive Particles (WIMPs) as candidates for dark matter. A possibility is discussed that new stable quarks and charged leptons exist and are hidden from detection, being bound in neutral dark atoms of composite dark matter. Stable -2 charged particles O^{--} are bound with primordial helium in O-helium (OHe) atoms, being specific nuclear interacting form of composite Warmer than Cold dark matter. Slowed down in the terrestrial matter, OHe is elusive for direct methods of underground dark matter detection based on the search for effects of nuclear recoil in WIMP-nucleus collisions. The positive results of DAMA experiments can be explained as annual modulation of radiative capture of O-helium by nuclei. In the framework of this approach test of DAMA results in detectors with other chemical content becomes a nontrivial task, while the experimental search of stable charged particles at LHC or in cosmic rays acquires a meaning of direct test for composite dark matter scenario.

Keywords: Elementary particles; dark matter; early universe; nuclear reactions; radiative capture; large-scale structure of universe.

PACS Nos.: include PACS Nos.

1. Introduction

According to the modern cosmology, the dark matter, corresponding to $\sim 25\%$ of the total cosmological density, is nonbaryonic and consists of new stable particles. Such particles (see e.g. ^{1,2,3,4,5} for review and reference) should be stable, saturate the measured dark matter density and decouple from plasma and radiation at least before the beginning of matter dominated stage. The easiest way to satisfy these conditions is to involve neutral elementary weakly interacting particles. However it is not the only particle physics solution for the dark matter problem and more evolved models of self-interacting dark matter are possible. In particular, new stable particles may possess new U(1) gauge charges and bind by Coulomb-like forces in composite dark matter species. Such dark atoms would look nonluminous, since

they radiate invisible light of U(1) photons. Historically mirror matter (see^{1,6} for review and references) seems to be the first example of such a nonluminous atomic dark matter.

Glashow's tera-helium⁷ has offered a new solution for dark atoms of dark matter. Tera-U-quarks with electric charge $+2/3$ formed stable (UUU) $+2$ charged "clusters" that formed with two -1 charged tera-electrons E neutral [(UUU)EE] tera-helium "atoms" that behaved like Weakly Interacting Massive Particles (WIMPs). The main problem for this solution was to suppress the abundance of positively charged species bound with ordinary electrons, which behave as anomalous isotopes of hydrogen or helium. This problem turned to be unresolvable⁸, since the model⁷ predicted stable tera-electrons E^- with charge -1 . As soon as primordial helium is formed in the Standard Big Bang Nucleosynthesis (SBBN) it captures all the free E^- in positively charged $(HeE)^+$ ion, preventing any further suppression of positively charged species. Therefore, in order to avoid anomalous isotopes overproduction, stable particles with charge -1 (and corresponding antiparticles) should be absent, so that stable negatively charged particles should have charge -2 only.

Elementary particle frames for heavy stable -2 charged species are provided by: (a) stable "antibaryons" $\bar{U}\bar{U}\bar{U}$ formed by anti- U quark of fourth generation^{9,10,12,13,14,15} (b) AC-leptons^{15,16,17,18}, predicted in the extension¹⁶ of standard model, based on the approach of almost-commutative geometry¹⁹. (c) Technileptons and anti-technibaryons²⁰ in the framework of walking technicolor models (WTC)^{21,22,23,24,25,26}. (d) Finally, stable charged clusters $\bar{u}_5\bar{u}_5\bar{u}_5$ of (anti)quarks \bar{u}_5 of 5th family can follow from the approach, unifying spins and charges^{27,28,29,30,31}. Since all these models also predict corresponding $+2$ charge antiparticles, cosmological scenario should provide mechanism of their suppression, what can naturally take place in the asymmetric case, corresponding to excess of -2 charge species, O^{--} . Then their positively charged antiparticles can effectively annihilate in the early Universe.

If new stable species belong to non-trivial representations of electroweak SU(2) group, sphaleron transitions at high temperatures can provide the relationship between baryon asymmetry and excess of -2 charge stable species, as it was demonstrated in the case of WTC in^{20,32,33,34,35,36}.

After it is formed in the Standard Big Bang Nucleosynthesis (SBBN), 4He screens the excessive O^{--} charged particles in composite $({}^4He^{++}O^{--})$ *O-helium* (*OHe*) "atoms"¹⁰.

In all the considered forms of O-helium, O^{--} behaves either as lepton or as specific "heavy quark cluster" with strongly suppressed hadronic interaction. Therefore O-helium interaction with matter is determined by nuclear interaction of He . These neutral primordial nuclear interacting species can play the role of a nontrivial form of strongly interacting dark matter^{37,38,39,40,41,42,43,44,45}, giving rise to a Warmer than Cold dark matter scenario^{11,32,33}.

Here after a brief review of possible charged constituents of dark atoms, we

concentrate on the properties of OHe atoms, their interaction with matter and qualitative picture of OHe cosmological evolution^{10,11,17,20,34,46,47} and observable effects. We show⁴⁸ that interaction of OHe with nuclei in underground detectors can explain positive results of dark matter searches in DAMA/NaI (see for review⁴⁹) and DAMA/LIBRA⁵⁰ experiments by annual modulations of radiative capture of O-helium, resolving the controversy between these results and the results of other experimental groups.

2. Charged constituents of composite dark matter

2.1. Problem of *tera-fermion composite dark matter*

Glashow's Tera-helium Universe was first inspiring example of the composite dark matter scenario. $SU(3)_c \times SU(2) \times SU(2)' \times U(1)$ gauge model⁷ was aimed to explain the origin of the neutrino mass and to solve the problem of strong CP-violation in QCD. New extra $SU(2)'$ symmetry acts on three heavy generations of *tera-fermions* linked with the light fermions by CP' transformation. $SU(2)'$ symmetry breaking at TeV scale makes *tera-fermions* much heavier than their light partners. Tera-fermion mass spectrum is the same as for light generations, but all the masses are scaled by the same factor of about 10^6 . Thus the masses of lightest heavy particles are in *tera-eV* (TeV) range, explaining their name.

Glashow's model⁷ takes into account that very heavy quarks Q (or antiquarks \bar{Q}) can form bound states with other heavy quarks (or antiquarks) due to their Coulomb-like QCD attraction, and the binding energy of these states substantially exceeds the binding energy of QCD confinement. Then stable (QQq) and (QQQ) baryons can exist.

According to⁷ primordial heavy quark U and heavy electron E are stable and may form a neutral $(UUUEE)$ "atom" with (UUU) hadron as nucleus and two E^- s as "electrons". The gas of such "tera-helium atoms" was proposed in⁷ as a candidate for a WIMP-like dark matter.

The problem of such scenario is an inevitable presence of "products of incomplete combustion" and the necessity to decrease their abundance.

Unfortunately, as it was shown in⁸, this picture of Tera-helium Universe can not be realized.

When ordinary ${}^4\text{He}$ is formed in Big Bang Nucleosynthesis, it binds all the free E^- into positively charged $({}^4\text{He}E^-)^+$ "ions". This puts Coulomb barrier for any successive E^-E^+ annihilation or any effective EU binding. It removes a possibility to suppress the abundance of unwanted *tera-particle* species (like (eE^+) , $({}^4\text{He}Ee)$ etc). For instance the remaining abundance of (eE^+) and $({}^4\text{He}E^-e)$ exceeds the terrestrial upper limit for anomalous hydrogen by 27 orders of magnitude⁸.

2.2. Composite dark matter from almost commutative geometry

The AC-model is based on the specific mathematical approach of unifying general relativity, quantum mechanics and gauge symmetry^{16,19}. This realization naturally

embeds the Standard model, both reproducing its gauge symmetry and Higgs mechanism with prediction of a Higgs boson mass. AC model is in some sense alternative to SUSY, GUT and superstring extension of Standard model. The AC-model¹⁶ extends the fermion content of the Standard model by two heavy particles, $SU(2)$ electro-weak singlets, with opposite electromagnetic charges. Each of them has its own antiparticle. Having no other gauge charges of Standard model, these particles (AC-fermions) behave as heavy stable leptons with charges $-2e$ and $+2e$, called A^{--} and C^{++} , respectively.

Similar to the Tera-helium Universe, AC-lepton relics from intermediate stages of a multi-step process towards a final (AC) atom formation must survive in the present Universe. In spite of the assumed excess of particles (A^{--} and C^{++}) the abundance of relic antiparticles (\bar{A}^{++} and \bar{C}^{--}) is not negligible. There may be also a significant fraction of A^{--} and C^{++} , which remains unbound after recombination process of these particles into (AC) atoms took place. As soon as 4He is formed in Big Bang nucleosynthesis, the primordial component of free anion-like AC-leptons (A^{--}) is mostly trapped in the first three minutes into a neutral O-helium atom ${}^4He^{++}A^{--}$. O-helium is able to capture free C^{++} creating (AC) atoms and releasing 4He back. In the same way the annihilation of antiparticles speeds up. C^{++} -O-helium reactions stop, when their timescale exceeds a cosmological time, leaving O-helium and C^{++} relics in the Universe. The catalytic reaction of O-helium with C^{++} in the dense matter bodies provides successive (AC) binding that suppresses terrestrial anomalous isotope abundance below the experimental upper limit. Due to screened charge of AC-atoms they have WIMP-like interaction with the ordinary matter. Such WIMPs are inevitably accompanied by a tiny component of nuclear interacting O-helium.

2.3. *Stable charged techniparticles in Walking Technicolor*

The minimal walking technicolor model^{21,22,23,24,25,26} has two techniquarks, i.e. up U and down D , that transform under the adjoint representation of an $SU(2)$ technicolor gauge group. The six Goldstone bosons UU , UD , DD and their corresponding antiparticles carry technibaryon number since they are made of two techniquarks or two anti-techniquarks. This means that if there is no processes violating the technibaryon number the lightest technibaryon will be stable.

The electric charges of UU , UD , and DD are given in general by $q + 1$, q , and $q - 1$ respectively, where q is an arbitrary real number. The model requires in addition the existence of a fourth family of leptons, i.e. a “new neutrino” ν' and a “new electron” ζ . Their electric charges are in terms of q respectively $(1 - 3q)/2$ and $(-1 - 3q)/2$.

There are three possibilities for a scenario of dark atoms of dark matter. The first one is to have an excess of $\bar{U}\bar{U}$ (charge -2). The technibaryon number TB is conserved and therefore UU (or $\bar{U}\bar{U}$) is stable. The second possibility is to have excess of ζ that also has -2 charge and is stable, if ζ is lighter than ν' and tech-

neutrino number L' is conserved. In the both cases stable particles with -2 electric charge have substantial relic densities and can capture ${}^4\text{He}^{++}$ nuclei to form a neutral techni-O-helium atom. Finally there is a possibility to have both L' and TB conserved. In this case, the dark matter would be composed of bound atoms (${}^4\text{He}^{++}\zeta^{--}$) and $(\zeta^{--}(UU)^{++})$. In the latter case the excess of ζ^{--} should be larger, than the excess of $(UU)^{++}$, so that WIMP-like $(\zeta^{--}(UU)^{++})$ is subdominant at the dominance of nuclear interacting techni-O-helium.

The technicolor and the Standard Model particles are in thermal equilibrium as long as the timescale of the weak (and color) interactions is smaller than the cosmological time. The sphalerons allow violation of TB , of baryon number B , of lepton number L and L' as long as the temperature of the Universe exceeds the electroweak scale. It was shown in²⁰ that there is a balance between the excess of techni(anti)baryons, $(\bar{U}\bar{U})^{--}$, technileptons ζ^{--} or of the both over the corresponding particles (UU and/or ζ^{++}) and the observed baryon asymmetry of the Universe. It was also shown the there are parameters of the model, at which this asymmetry has proper sign and value, explaining the dark matter density.

2.4. Stable particles of 4th generation matter

Modern precision data on the parameters of the Standard model do not exclude⁵¹ the existence of the 4th generation of quarks and leptons. The 4th generation follows from heterotic string phenomenology and its difference from the three known light generations can be explained by a new conserved charge, possessed only by its quarks and leptons^{9,10,52,53,54}. Strict conservation of this charge makes the lightest particle of 4th family (neutrino) absolutely stable, but it was shown in^{52,53,54} that this neutrino cannot be the dominant form of the dark matter. The same conservation law requires the lightest quark to be long living^{9,10}. In principle the lifetime of U can exceed the age of the Universe, if $m_U < m_D$ ^{9,10}. Provided that sphaleron transitions establish excess of \bar{U} antiquarks at the observed baryon asymmetry $(\bar{U}\bar{U}\bar{U})$ can be formed and bound with ${}^4\text{He}$ in atom-like state of O-helium¹⁵.

In the successive discussion of OHe dark matter we generally don't specify the type of -2 charged particle, denoting it as O^{--} .

3. OHe atoms and their interaction with nuclei

The structure of OHe atom follows from the general analysis of the bound states of O^{--} with nuclei.

Consider a simple model^{55,56,57}, in which the nucleus is regarded as a sphere with uniform charge density and in which the mass of the O^{--} is assumed to be much larger than that of the nucleus. Spin dependence is also not taken into account so that both the particle and nucleus are considered as scalars. Then the

6 *M.Yu.KHLOPOV*

Hamiltonian is given by

$$H = \frac{p^2}{2Am_p} - \frac{ZZ_x\alpha}{2R} + \frac{ZZ_x\alpha}{2R} \cdot \left(\frac{r}{R}\right)^2, \quad (1)$$

for short distances $r < R$ and

$$H = \frac{p^2}{2Am_p} - \frac{ZZ_x\alpha}{R}, \quad (2)$$

for long distances $r > R$, where α is the fine structure constant, $R = d_o A^{1/3} \sim 1.2 A^{1/3} / (200 \text{ MeV})$ is the nuclear radius, Z is the electric charge of nucleus and $Z_x = 2$ is the electric charge of negatively charged particle X^{--} . Since $Am_p \ll M_X$ the reduced mass is $1/m = 1/(Am_p) + 1/M_X \approx 1/(Am_p)$.

For small nuclei the Coulomb binding energy is like in hydrogen atom and is given by

$$E_b = \frac{1}{2} Z^2 Z_x^2 \alpha^2 Am_p. \quad (3)$$

For large nuclei X^{--} is inside nuclear radius and the harmonic oscillator approximation is valid for the estimation of the binding energy

$$E_b = \frac{3}{2} \left(\frac{ZZ_x\alpha}{R} - \frac{1}{R} \left(\frac{ZZ_x\alpha}{Am_p R} \right)^{1/2} \right). \quad (4)$$

For the intermediate regions between these two cases with the use of trial function of the form $\psi \sim e^{-\gamma r/R}$ variational treatment of the problem^{55,56,57} gives

$$E_b = \frac{1}{Am_p R^2} F(ZZ_x\alpha Am_p R), \quad (5)$$

where the function $F(a)$ has limits

$$F(a \rightarrow 0) \rightarrow \frac{1}{2} a^2 - \frac{2}{5} a^4 \quad (6)$$

and

$$F(a \rightarrow \infty) \rightarrow \frac{3}{2} a - (3a)^{1/2}, \quad (7)$$

where $a = ZZ_x\alpha Am_p R$. For $0 < a < 1$ the Coulomb model gives a good approximation, while at $2 < a < \infty$ the harmonic oscillator approximation is appropriate.

In the case of OHe $a = ZZ_x\alpha Am_p R \leq 1$, what proves its Bohr-atom-like structure, assumed in^{10,12,15,20,34,35,36}. The radius of Bohr orbit in these “atoms”^{10,11} $r_o \sim 1/(Z_o Z_{He} \alpha m_{He}) \approx 2 \cdot 10^{-13} \text{ cm}$. However, the size of He nucleus, rotating around O^{--} in this Bohr atom, turns out to be of the order and even a bit larger than the radius r_o of its Bohr orbit, and the corresponding correction to the binding energy due to non-point-like charge distribution in He is significant.

Bohr atom like structure of OHe seems to provide a possibility to use the results of atomic physics for description of OHe interaction with matter. However, the situation is much more complicated. OHe atom is similar to the hydrogen, in which

electron is hundreds times heavier, than proton, so that it is proton shell that surrounds "electron nucleus". Nuclei that interact with such "hydrogen" would interact first with strongly interacting "protonic" shell and such interaction can hardly be treated in the framework of perturbation theory. Moreover in the description of OHe interaction the account for the finite size of He, which is even larger than the radius of Bohr orbit, is important. One should consider, therefore, the analysis, presented below, as only a first step approaching true nuclear physics of OHe.

The approach of^{11,32} assumes the following picture of OHe interaction with nuclei: OHe is a neutral atom in the ground state, perturbed by Coulomb and nuclear forces of the approaching nucleus. The sign of OHe polarization changes with the distance: at larger distances Stark-like effect takes place - nuclear Coulomb force polarizes OHe so that nucleus is attracted by the induced dipole moment of OHe, while as soon as the perturbation by nuclear force starts to dominate the nucleus polarizes OHe in the opposite way so that He is situated more close to the nucleus, resulting in the repulsive effect of the helium shell of OHe. When helium is completely merged with the nucleus the interaction is reduced to the oscillatory potential of O^{--} with homogeneously charged merged nucleus with the charge $Z+2$.

Therefore OHe-nucleus potential has qualitative feature, presented on Fig. 1: the potential well U_3 at large distances (regions III-IV) is changed by a potential wall U_2 in region II. The existence of this potential barrier causes suppression of reactions with transition of OHe-nucleus system to levels in the potential well U_1 of the region I. It results in the dominance of elastic scattering while transitions to levels in the shallow well (regions III-IV) should dominate in reactions of OHe-nucleus capture.

On the other hand, O-helium, being an α -particle with screened electric charge, can catalyze nuclear transformations, which can influence primordial light element abundance and cause primordial heavy element formation. It is especially important for quantitative estimation of role of OHe in Big Bang Nucleosynthesis and in stellar evolution. These effects need a special detailed and complicated study and this work is under way. Our first steps in the approach to OHe nuclear physics seem to support the qualitative picture of OHe cosmological evolution described in^{10,11,17,20,32,34,46} and based on the dominant role of elastic collisions in OHe interaction with baryonic matter.

4. Some features of O-helium Universe

4.1. Large Scale structure formation by OHe dark matter

Due to elastic nuclear interactions of its helium constituent with nuclei in the cosmic plasma, the O-helium gas is in thermal equilibrium with plasma and radiation on the Radiation Dominance (RD) stage, while the energy and momentum transfer from plasma is effective. The radiation pressure acting on the plasma is then transferred to density fluctuations of the O-helium gas and transforms them in acoustic waves at scales up to the size of the horizon.

At temperature $T < T_{od} \approx 1S_3^{2/3}$ eV the energy and momentum transfer from

8 *M.Yu.KHLOPOV*

baryons to O-helium is not effective^{10,20} because

$$n_B \langle \sigma v \rangle (m_p/m_o)t < 1,$$

where m_o is the mass of the *OHe* atom and $S_3 = m_o/(1 \text{ TeV})$. Here

$$\sigma \approx \sigma_o \sim \pi r_o^2 \approx 10^{-25} \text{ cm}^2, \quad (8)$$

and $v = \sqrt{2T/m_p}$ is the baryon thermal velocity. Then O-helium gas decouples from plasma. It starts to dominate in the Universe after $t \sim 10^{12} \text{ s}$ at $T \leq T_{RM} \approx 1 \text{ eV}$ and O-helium “atoms” play the main dynamical role in the development of gravitational instability, triggering the large scale structure formation. The composite nature of O-helium determines the specifics of the corresponding dark matter scenario.

At $T > T_{RM}$ the total mass of the *OHe* gas with density $\rho_d = (T_{RM}/T)\rho_{tot}$ is equal to

$$M = \frac{4\pi}{3} \rho_d t^3 = \frac{4\pi}{3} \frac{T_{RM}}{T} m_{Pl} \left(\frac{m_{Pl}}{T}\right)^2$$

within the cosmological horizon $l_h = t$. In the period of decoupling $T = T_{od}$, this mass depends strongly on the O-helium mass S_3 and is given by²⁰

$$M_{od} = \frac{T_{RM}}{T_{od}} m_{Pl} \left(\frac{m_{Pl}}{T_{od}}\right)^2 \approx 2 \cdot 10^{44} S_3^{-2} \text{ g} = 10^{11} S_3^{-2} M_\odot, \quad (9)$$

where M_\odot is the solar mass. O-helium is formed only at T_o and its total mass within the cosmological horizon in the period of its creation is $M_o = M_{od}(T_{od}/T_o)^3 = 10^{37} \text{ g}$.

On the RD stage before decoupling, the Jeans length λ_J of the *OHe* gas was restricted from below by the propagation of sound waves in plasma with a relativistic equation of state $p = \epsilon/3$, being of the order of the cosmological horizon and equal to $\lambda_J = l_h/\sqrt{3} = t/\sqrt{3}$. After decoupling at $T = T_{od}$, it falls down to $\lambda_J \sim v_o t$, where $v_o = \sqrt{2T_{od}/m_o}$. Though after decoupling the Jeans mass in the *OHe* gas correspondingly falls down

$$M_J \sim v_o^3 M_{od} \sim 3 \cdot 10^{-14} M_{od},$$

one should expect a strong suppression of fluctuations on scales $M < M_o$, as well as adiabatic damping of sound waves in the RD plasma for scales $M_o < M < M_{od}$. It can provide some suppression of small scale structure in the considered model for all reasonable masses of O-helium. The significance of this suppression and its effect on the structure formation needs a special study in detailed numerical simulations. In any case, it can not be as strong as the free streaming suppression in ordinary Warm Dark Matter (WDM) scenarios, but one can expect that qualitatively we deal with Warmer Than Cold Dark Matter model.

At temperature $T < T_{od} \approx 1 S_3^{2/3} \text{ keV}$ the energy and momentum transfer from baryons to O-helium is not effective^{10,11,32} and O-helium gas decouples from plasma. It starts to dominate in the Universe after $t \sim 10^{12} \text{ s}$ at $T \leq T_{RM} \approx 1 \text{ eV}$

and O-helium “atoms” play the main dynamical role in the development of gravitational instability, triggering the large scale structure formation. The composite nature of O-helium determines the specifics of the corresponding warmer than cold dark matter scenario.

Being decoupled from baryonic matter, the OHe gas does not follow the formation of baryonic astrophysical objects (stars, planets, molecular clouds...) and forms dark matter halos of galaxies. It can be easily seen that O-helium gas is collisionless for its number density, saturating galactic dark matter. Taking the average density of baryonic matter one can also find that the Galaxy as a whole is transparent for O-helium in spite of its nuclear interaction. Only individual baryonic objects like stars and planets are opaque for it.

4.2. Anomalous component of cosmic rays

O-helium atoms can be destroyed in astrophysical processes, giving rise to acceleration of free O^{--} in the Galaxy.

O-helium can be ionized due to nuclear interaction with cosmic rays^{10,36}. Estimations^{10,58} show that for the number density of cosmic rays $n_{CR} = 10^{-9} \text{ cm}^{-3}$ during the age of Galaxy a fraction of about 10^{-6} of total amount of OHe is disrupted irreversibly, since the inverse effect of recombination of free O^{--} is negligible. Near the Solar system it leads to concentration of free O^{--} $n_O = 3 \cdot 10^{-10} S_3^{-1} \text{ cm}^{-3}$. After OHe destruction free O^{--} have momentum of order $p_O \cong \sqrt{2 \cdot m_o \cdot I_o} \cong 2 \text{ GeV} S_3^{1/2}$ and velocity $v/c \cong 2 \cdot 10^{-3} S_3^{-1/2}$ and due to effect of Solar modulation these particles initially can hardly reach Earth^{33,58}. Their acceleration by Fermi mechanism or by the collective acceleration forms power spectrum of O^{--} component at the level of $O/p \sim n_O/n_g = 3 \cdot 10^{-10} S_3^{-1}$, where $n_g \sim 1 \text{ cm}^{-3}$ is the density of baryonic matter gas.

At the stage of red supergiant stars have the size $\sim 10^{15} \text{ cm}$ and during the period of this stage $\sim 3 \cdot 10^{15} \text{ s}$, up to $\sim 10^{-9} S_3^{-1}$ of O-helium atoms per nucleon can be captured^{33,58}. In the Supernova explosion these OHe atoms are disrupted in collisions with particles in the front of shock wave and acceleration of free O^{--} by regular mechanism gives the corresponding fraction in cosmic rays. However, this picture needs detailed analysis, based on the development of OHe nuclear physics and numerical studies of OHe evolution in the stellar matter.

If these mechanisms of O^{--} acceleration are effective, the anomalous low Z/A component of -2 charged O^{--} can be present in cosmic rays at the level $O/p \sim n_O/n_g \sim 10^{-9} S_3^{-1}$, and be within the reach for PAMELA and AMS02 cosmic ray experiments.

In the framework of Walking Technicolor model the excess of both stable ζ^{--} and $(UU)^{++}$ is possible³³, the latter being two-three orders of magnitude smaller, than the former. It leads to the two-component composite dark matter scenario with the dominant OHe accompanied by a subdominant WIMP-like component of $(\zeta^{--}(UU)^{++})$ bound systems. Technibaryons and technileptons can be metastable

and decays of ζ^{--} and $(UU)^{++}$ can provide explanation for anomalies, observed in high energy cosmic positron spectrum by PAMELA and in high energy electron spectrum by FERMI and ATIC.

4.3. Positron annihilation and gamma lines in galactic bulge

Inelastic interaction of O-helium with the matter in the interstellar space and its de-excitation can give rise to radiation in the range from few keV to few MeV. In the galactic bulge with radius $r_b \sim 1$ kpc the number density of O-helium can reach the value $n_o \approx 3 \cdot 10^{-3}/S_3 \text{ cm}^{-3}$ and the collision rate of O-helium in this central region was estimated in ³⁶: $dN/dt = n_o^2 \sigma v_h 4\pi r_b^3/3 \approx 3 \cdot 10^{42} S_3^{-2} \text{ s}^{-1}$. At the velocity of $v_h \sim 3 \cdot 10^7 \text{ cm/s}$ energy transfer in such collisions is $\Delta E \sim 1 \text{ MeV } S_3$. These collisions can lead to excitation of O-helium. If 2S level is excited, pair production dominates over two-photon channel in the de-excitation by $E0$ transition and positron production with the rate $3 \cdot 10^{42} S_3^{-2} \text{ s}^{-1}$ is not accompanied by strong gamma signal. According to ⁵⁹ this rate of positron production for $S_3 \sim 1$ is sufficient to explain the excess in positron annihilation line from bulge, measured by INTEGRAL (see ⁶⁰ for review and references). If OHe levels with nonzero orbital momentum are excited, gamma lines should be observed from transitions ($n > m$) $E_{nm} = 1.598 \text{ MeV}(1/m^2 - 1/n^2)$ (or from the similar transitions corresponding to the case $I_o = 1.287 \text{ MeV}$) at the level $3 \cdot 10^{-4} S_3^{-2} (\text{cm}^2 \text{ s MeV ster})^{-1}$.

It should be noted that the nuclear cross section of the O-helium interaction with matter escapes the severe constraints^{43,44,45} on strongly interacting dark matter particles (SIMPs)^{37,38,39,40,41,42,43,44,45} imposed by the XQC experiment^{61,62}. Therefore, a special strategy of direct O-helium search is needed, as it was proposed in ⁶³.

4.4. O-helium in the terrestrial matter

The evident consequence of the O-helium dark matter is its inevitable presence in the terrestrial matter, which appears opaque to O-helium and stores all its in-falling flux.

After they fall down terrestrial surface, the in-falling OHe particles are effectively slowed down due to elastic collisions with matter. Then they drift, sinking down towards the center of the Earth with velocity

$$V = \frac{g}{n\sigma v} \approx 80 S_3 A_{med}^{1/2} \text{ cm/s.} \quad (10)$$

Here $A_{med} \sim 30$ is the average atomic weight in terrestrial surface matter, $n = 2.4 \cdot 10^{24}/A$ is the number of terrestrial atomic nuclei, σv is the rate of nuclear collisions and $g = 980 \text{ cm/s}^2$.

Near the Earth's surface, the O-helium abundance is determined by the equilibrium between the in-falling and down-drifting fluxes.

At a depth L below the Earth's surface, the drift timescale is $t_{dr} \sim L/V$, where $V \sim 400 S_3 \text{ cm/s}$ is the drift velocity and $m_o = S_3 \text{ TeV}$ is the mass of O-helium. It

means that the change of the incoming flux, caused by the motion of the Earth along its orbit, should lead at the depth $L \sim 10^5$ cm to the corresponding change in the equilibrium underground concentration of *OHe* on the timescale $t_{dr} \approx 2.5 \cdot 10^2 S_3^{-1}$ s.

The equilibrium concentration, which is established in the matter of underground detectors at this timescale, is given by

$$n_{oE} = n_{oE}^{(1)} + n_{oE}^{(2)} \cdot \sin(\omega(t - t_0)) \quad (11)$$

with $\omega = 2\pi/T$, $T = 1yr$ and t_0 the phase. So, there is a averaged concentration given by

$$n_{oE}^{(1)} = \frac{n_o}{320 S_3 A_{med}^{1/2}} V_h \quad (12)$$

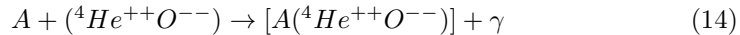
and the annual modulation of concentration characterized by the amplitude

$$n_{oE}^{(2)} = \frac{n_o}{640 S_3 A_{med}^{1/2}} V_E. \quad (13)$$

Here V_h -speed of Solar System (220 km/s), V_E -speed of Earth (29.5 km/s) and $n_0 = 3 \cdot 10^{-4} S_3^{-1} \text{ cm}^{-3}$ is the local density of O-helium dark matter.

5. OHe in the underground detectors

The explanation^{11,48} of the results of DAMA/NaI⁴⁹ and DAMA/LIBRA⁵⁰ experiments is based on the idea that OHe, slowed down in the matter of detector, can form a few keV bound state with nucleus, in which OHe is situated **beyond** the nucleus. Therefore the positive result of these experiments is explained by annual modulation in reaction of radiative capture of OHe



by nuclei in DAMA detector.

To simplify the solution of Schrodinger equation the potential was approximated in^{11,32} by a rectangular potential, presented on Fig. 1. Solution of Schrodinger equation determines the condition, under which a low-energy OHe-nucleus bound state appears in the shallow well of the region III and the range of nuclear parameters was found, at which OHe-sodium binding energy is in the interval 2-4 keV.

The rate of radiative capture of OHe by nuclei can be calculated^{11,48} with the use of the analogy with the radiative capture of neutron by proton with the account for: i) absence of M1 transition that follows from conservation of orbital momentum and ii) suppression of E1 transition in the case of OHe. Since OHe is isoscalar, isovector E1 transition can take place in OHe-nucleus system only due to effect of isospin nonconservation, which can be measured by the factor $f = (m_n - m_p)/m_N \approx 1.4 \cdot 10^{-3}$, corresponding to the difference of mass of neutron, m_n , and proton, m_p , relative to the mass of nucleon, m_N . In the result the rate of OHe radiative capture

by nucleus with atomic number A and charge Z to the energy level E in the medium with temperature T is given by

$$\sigma v = \frac{f\pi\alpha}{m_p^2} \frac{3}{\sqrt{2}} \left(\frac{Z}{A}\right)^2 \frac{T}{\sqrt{Am_p E}}. \quad (15)$$

Formation of OHe-nucleus bound system leads to energy release of its binding energy, detected as ionization signal. In the context of our approach the existence of annual modulations of this signal in the range 2-6 keV and absence of such effect at energies above 6 keV means that binding energy E_{Na} of Na-OHe system in DAMA experiment should not exceed 6 keV, being in the range 2-4 keV. The amplitude of annual modulation of ionization signal can reproduce the result of DAMA/NaI and DAMA/LIBRA experiments for $E_{Na} = 3$ keV. The account for energy resolution in DAMA experiments⁷¹ can explain the observed energy distribution of the signal from monochromatic photon (with $E_{Na} = 3$ keV) emitted in OHe radiative capture.

At the corresponding nuclear parameters there is no binding of OHe with iodine and thallium¹¹.

It should be noted that the results of DAMA experiment exhibit also absence of annual modulations at the energy of MeV-tens MeV. Energy release in this range should take place, if OHe-nucleus system comes to the deep level inside the nucleus. This transition implies tunneling through dipole Coulomb barrier and is suppressed below the experimental limits.

For the chosen range of nuclear parameters, reproducing the results of DAMA/NaI and DAMA/LIBRA, the results¹¹ indicate that there are no levels in the OHe-nucleus systems for heavy nuclei. In particular, there are no such levels in Xe, what seem to prevent direct comparison with DAMA results in XENON100 experiment⁶⁷. The existence of such level in Ge and the comparison with the results of CDMS^{64,65,66} and CoGeNT⁶⁸ experiments need special study. According to¹¹ OHe should bind with O and Ca, what is of interest for interpretation of the signal, observed in CRESST-II experiment⁶⁹.

In the thermal equilibrium OHe capture rate is proportional to the temperature. Therefore it looks like it is suppressed in cryogenic detectors by a factor of order 10^{-4} . However, for the size of cryogenic devices less, than few tens meters, OHe gas in them has the thermal velocity of the surrounding matter and this velocity dominates in the relative velocity of OHe-nucleus system. It gives the suppression relative to room temperature only $\sim m_A/m_o$. Then the rate of OHe radiative capture in cryogenic detectors is given by Eq.(15), in which room temperature T is multiplied by factor m_A/m_o . Note that in the case of $T = 70$ K in CoGeNT experiment relative velocity is determined by the thermal velocity of germanium nuclei, what leads to enhancement relative to cryogenic germanium detectors.

6. Conclusions

The existence of heavy stable particles is one of the popular solutions for the dark matter problem. Usually they are considered to be electrically neutral. But po-

tentially dark matter can be formed by stable heavy charged particles bound in neutral atom-like states by Coulomb attraction. Analysis of the cosmological data and atomic composition of the Universe gives the constraints on the particle charge showing that only -2 charged constituents, being trapped by primordial helium in neutral O-helium states, can avoid the problem of overproduction of the anomalous isotopes of chemical elements, which are severely constrained by observations. Cosmological model of O-helium dark matter can even explain puzzles of direct dark matter searches.

The proposed explanation is based on the mechanism of low energy binding of OHe with nuclei. Within the uncertainty of nuclear physics parameters there exists a range at which OHe binding energy with sodium is in the interval 2-4 keV. Annual modulation in radiative capture of OHe to this bound state leads to the corresponding energy release observed as an ionization signal in DAMA/NaI and DAMA/LIBRA experiments.

With the account for high sensitivity of the numerical results to the values of nuclear parameters and for the approximations, made in the calculations, the presented results can be considered only as an illustration of the possibility to explain puzzles of dark matter search in the framework of composite dark matter scenario. An interesting feature of this explanation is a conclusion that the ionization signal may be absent in detectors containing light (e.g. ${}^3\text{He}$) or heavy (e.g. Xe) elements. Therefore test of results of DAMA/NaI and DAMA/LIBRA experiments by other experimental groups can become a very nontrivial task. Recent indications to positive result in the matter of CRESST detector⁶⁹, in which OHe binding is expected together with absence of signal in xenon detector⁶⁷, may qualitatively favor the presented approach. For the same chemical content an order of magnitude suppression in cryogenic detectors can explain why indications to positive effect in CoGeNT experiment⁶⁸ can be compatible with the constraints of CDMS experiment.

An inevitable consequence of the proposed explanation is appearance in the matter of underground detectors anomalous superheavy isotopes, having the mass roughly by m_o larger, than ordinary isotopes of the corresponding elements.

It is interesting to note that in the framework of the presented approach positive result of experimental search for WIMPs by effect of their nuclear recoil would be a signature for a multicomponent nature of dark matter. Such OHe+WIMPs multicomponent dark matter scenarios naturally follow from AC model¹⁷ and can be realized in models of Walking technicolor³³.

Stable -2 charge states (O^{--}) can be elementary like AC-leptons or technileptons, or look like technibaryons. The latter, composed of techniquarks, reveal their structure at much higher energy scale and should be produced at LHC as elementary species. The signature for AC leptons and techniparticles is unique and distinctive what allows to separate them from other hypothetical exotic particles.

Since simultaneous production of three $U\bar{U}$ pairs and their conversion in two doubly charged quark clusters UUU is suppressed, the only possibility to test the models of composite dark matter from 4th generation in the collider experiments

is a search for production of stable hadrons containing single U or \bar{U} like Uud and $\bar{U}u/\bar{U}d$.

The presented approach sheds new light on the physical nature of dark matter. Specific properties of dark atoms and their constituents contain distinct features, by which they can be distinguished from other recent approaches to this problem^{72,73,74,75,76,77,78,79,80,81,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96}, and are challenging for the experimental search. The development of quantitative description of OHe interaction with matter confronted with the experimental data will provide the complete test of the composite dark matter model. It challenges search for stable double charged particles at accelerators and cosmic rays as direct experimental probe for charged constituents of dark atoms of dark matter.

Acknowledgments

I express my gratitude to K.M. Belotsky, D. Fargion, C. Kouvaris, A.G. Mayorov, E. Yu. Soldatov and C. Stephan for collaboration in obtaining the original results and to J.R. Cudell and A.S. Romaniouk for discussions.

References

1. M.Yu. Khlopov *Cosmoparticle physics* (World Scientific, Singapore, 1999).
2. M.Yu. Khlopov in *Cosmion-94*, Eds. M.Yu.Khlopov et al. (Editions frontieres, 1996) P. 67.
3. M. Y. Khlopov, *Bled Workshops in Physics* **7**, 51 (2006).
4. M. Y. Khlopov, *Bled Workshops in Physics* **8**, 114 (2007).
5. M.Yu. Khlopov *Fundamentals of Cosmoparticle physics* (CISP-Springer, Cambridge, 2011).
6. L. B. Okun, *Phys. Usp.* **50**, 380 (2007).
7. S. L. Glashow, arXiv:hep-ph/0504287.
8. D. Fargion and M. Khlopov, arXiv:hep-ph/0507087.
9. K.M.Belotsky *et al*, *Gravitation and Cosmology* **11**, 3 (2005)
10. M.Yu. Khlopov, *JETP Lett.* **83**, 1 (2006).
11. M. Y. Khlopov, A. G. Mayorov and E. Y. Soldatov, *J. Phys.: Conf. Ser.* **309**, 012013 (2011).
12. K. Belotsky *et al*, arXiv:astro-ph/0602261.
13. K. Belotsky *et al*, *Gravitation and Cosmology* **12**, 1 (2006).
14. K. Belotsky *et al*, in *The Physics of Quarks: New Research. (Horizons in World Physics, V.265)* Eds. N. L. Watson and T. M. Grant, (NOVA Publishers, Hauppauge NY, 2009), p.19.
15. M. Y. Khlopov, arXiv:astro-ph/0607048.
16. C. A. Stephan, arXiv:hep-th/0509213.
17. D. Fargion *et al*, *Class. Quantum Grav.* **23**, 7305 (2006).
18. M. Y. Khlopov and C. A. Stephan, arXiv:astro-ph/0603187.
19. A. Connes *Noncommutative Geometry* (Academic Press, London and San Diego, 1994).
20. M. Y. Khlopov and C. Kouvaris, *Phys. Rev. D* **77**, 065002 (2008).
21. F. Sannino and K. Tuominen, *Phys. Rev. D* **71**, 051901 (2005).
22. D. K. Hong *et al*, *Phys. Lett. B* **597**, 89 (2004).
23. D. D. Dietrich *et al*, *Phys. Rev. D* **72**, 055001 (2005).

24. D. D. Dietrich *et al*, *Phys. Rev. D* **73**, 037701 (2006).
25. S. B. Gudnason *et al*, *Phys. Rev. D* **73**, 115003 (2006).
26. S. B. Gudnason *et al*, *Phys. Rev. D* **74**, 095008 (2006).
27. N.S. Mankoč Borštnik, *Bled Workshops in Physics* **11**, 105 (2010).
28. A. Borštnik Bračič, N.S. Mankoč Borštnik, *Phys. Rev. D* **74**, 073013 (2006).
29. N.S. Mankoč Borštnik, *Mod. Phys. Lett. A* **10**, 587 (1995).
30. N.S. Mankoč Borštnik, *Int. J. Theor. Phys.* **40**, 315 (2001).
31. G. Bregar, M. Breskvar, D. Lukman, N.S. Mankoč Borštnik, *New J. of Phys.* **10**, 093002 (2008).
32. M. Y. Khlopov, A. G. Mayorov and E. Y. Soldatov, *Bled Workshops in Physics* **11**, 73 (2010).
33. M. Y. Khlopov and C. Kouvaris, *Phys. Rev. D* **78**, 065040 (2008).
34. M. Y. Khlopov, *AIP Conf. Proc.* **1241**, 388 (2010).
35. M. Y. Khlopov, A. G. Mayorov and E. Y. Soldatov, *Int. J. Mod. Phys. D* **19**, 1385 (2010).
36. M. Y. Khlopov, arXiv:0806.3581 [astro-ph].
37. C. B. Dover *et al*, *Phys. Rev. Lett.* **42**, 1117 (1979).
38. S. Wolfram, *Phys. Lett. B* **82**, 65 (1979).
39. G. D. Starkman *et al*, *Phys. Rev. D* **41**, 3594 (1990).
40. D. Javorsek *et al*, *Phys. Rev. Lett.* **87**, 231804 (2001).
41. S. Mitra, *Phys. Rev. D* **70**, 103517 (2004).
42. G. D. Mack *et al*, *Phys. Rev. D* **76**, 043523 (2007).
43. B.D. Wandelt *et al.*, arXiv:astro-ph/0006344.
44. P. C. McGuire and P. J. Steinhardt, arXiv:astro-ph/0105567.
45. G. Zaharijas and G. R. Farrar, *Phys. Rev. D* **72**, 083502 (2005).
46. M. Y. Khlopov, arXiv:0801.0167 [astro-ph].
47. M. Y. Khlopov, arXiv:0801.0169 [astro-ph].
48. M. Y. Khlopov, A. G. Mayorov and E. Y. Soldatov, *Bled Workshops in Physics* **11**, 185 (2010).
49. R. Bernabei *et al.*, *Rivista Nuovo Cimento* **26**, 1 (2003)
50. R. Bernabei *et al.* [DAMA Collaboration], *Eur.Phys.J C* **56**, 333 (2008)
51. M. Maltoni *et al.*, *Phys. Lett. B* **476**, 107 (2000)
52. K.M.Belotsky, M.Yu.Khlopov and K.I.Shibaev, *Gravitation and Cosmology Supplement* **6**, 140 (2000).
53. K.M.Belotsky *et al.*, *Gravitation and Cosmology* **11**, 16 (2005).
54. K.M.Belotsky *et al.*, *Phys.Atom.Nucl.* **71**, 147 (2008).
55. R. N. Cahn and S. L. Glashow, *Science* **213**, 607 (1981).
56. M. Pospelov, *Phys. Rev. Lett.* **98**, 231301 (2007).
57. K. Kohri and F. Takayama, *Phys. Rev. D* **76**, 063507 (2007).
58. K.M.Belotsky, A.G.Mayorov, M.Yu.Khlopov. Charged particles of dark matter in cosmic rays. ISBN 978-5-7262-1280-7, Scientific Session NRNU MEPhI-2010, V.4, P.127
59. D. P. Finkbeiner and N. Weiner, *Phys. Rev. D* **76**, 083519 (2007)
60. B. J. Teegarden *et al*, *Astrophys. J.* **621**, 296 (2005)
61. D. McCammon *et al*, *Nucl. Instrum. Methods A* **370**, 266 (1996);
62. D. McCammon *et al*, *Astrophys. J.* **576**, 188 (2002).
63. K. Belotsky *et al*, arXiv:astro-ph/0606350.
64. D. S. Akerib *et al.* [CDMS Collaboration], *Phys. Rev. Lett.* **96**, 011302 (2006).
65. Z. Ahmed *et al.* [CDMS Collaboration], *Phys. Rev. Lett.* **102**, 011301 (2009).
66. N. Mirabolfathi *et al.* [CDMS Collaboration], *Nucl. Instrum. Methods A* **559**, 417 (2006).

67. E. Aprile *et al.* [XENON100 Collaboration], *Phys. Rev. Lett.* **105**, 131302 (2010).
68. C. E. Aalseth *et al.*, *Phys. Rev. Lett.* **107**, 141301 (2011).
69. G. Angloher *et al.*, arXiv:1109.0702 [astro-ph.CO].
70. M. Yu. Khlopov, A. G. Mayorov, E.Yu. Soldatov, *Bled Workshops in Physics* **10**, 79 (2009).
71. R. Bernabei *et al.* [DAMA Collaboration], *Nucl. Instrum. Methods A* **592**, 297 (2008)
72. F. Petriello and K. M. Zurek, *JHEP* **0809**, 047 (2008).
73. R. Foot, *Phys. Rev. D* **78**, 043529 (2008).
74. J. L. Feng, J. Kumar and L. E. Strigari, *Phys. Lett. B* **670**, 37 (2008).
75. J. L. Feng, J. Kumar, J. Learned and L. E. Strigari, *JCAP* **0901**, 032 (2009).
76. E. M. Drobyshevski, *Mod. Phys. Lett. A* **24**, 177 (2009).
77. B. Feldstein, A. L. Fitzpatrick and E. Katz, *JCAP* **1001**, 020 (2010).
78. Y. Bai and P. J. Fox, *JHEP* **0911**, 052 (2009).
79. B. Feldstein *et al.*, *JCAP* **1003**, 029 (2010).
80. A. L. Fitzpatrick, D. Hooper and K. M. Zurek, *Phys. Rev. D* **81**, 115005 (2010).
81. S. Andreas *et al.*, *Phys. Rev. D* **82**, 043522 (2010).
82. D. S. M. Alves *et al.*, *JHEP* **1006**, 113 (2010).
83. V. Barger, M. McCaskey and G. Shaughnessy, *Phys. Rev. D* **82**, 035019 (2010).
84. C. Savage *et al.*, *Phys. Rev. D* **83**, 055002 (2011).
85. D. Hooper *et al.*, *Phys. Rev. D* **82**, 123509 (2010).
86. S. Chang, R. F. Lang and N. Weiner, *Phys. Rev. Lett.* **106**, 011301 (2011).
87. S. Chang, N. Weiner and I. Yavin, *Phys. Rev. D* **82**, 125011 (2010).
88. V. Barger, W. Y. Keung and D. Marfatia, *Phys. Lett. B* **696**, 74 (2011).
89. A. L. Fitzpatrick and K. M. Zurek, arXiv:1007.5325 [hep-ph].
90. T. Banks, J. F. Fortin and S. Thomas, arXiv:1007.5515 [hep-ph].
91. B. Feldstein, P. W. Graham and S. Rajendran, *Phys. Rev. D* **82**, 075019 (2010).
92. G. B. Gelmini, *Int. J. Mod. Phys. A* **23**, 4273 (2008).
93. E. Aprile, S. Profumo, *New J. of Phys.* **11**, 105002 (2009).
94. J. L. Feng, *Ann. Rev. Astron. Astrophys.* **48**, 495 (2010).
95. De-Chang Dai, K. Freese, D. Stojkovic, *JCAP* **0906**, 023 (2009).
96. Jia-Ming Zheng *et al.*, *Nucl. Phys. B* **854**, 350 (2012).

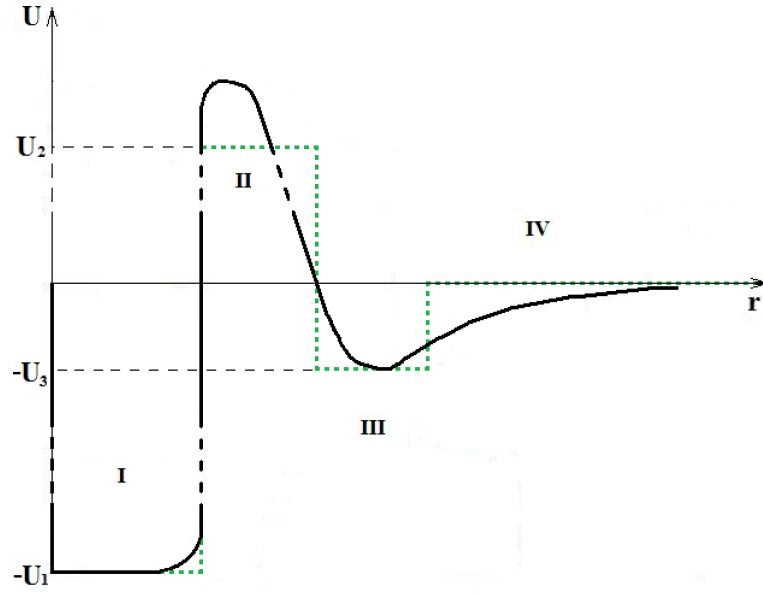


Fig. 1. The potential of OHe-nucleus system and its rectangular well approximation.